Extraordinary Phenomenology from Warped Flavor Triviality

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Anarchic warped extra dimensional models provide a solution to the hierarchy problem. They can also account for the observed flavor hierarchies, but only at the expense of little hierarchy and CP problems, which naturally require a Kaluza-Klein (KK) scale beyond the LHC reach. We have recently shown that when flavor issues are decoupled, and assumed to be solved by UV physics, the framework's parameter space greatly opens. Given the possibility of a lower KK scale and composite light quarks, this class of flavor triviality models enjoys a rather exceptional phenomenology, which is the focus of this letter. We also revisit the anarchic RS EDM problem, which requires $m_{KK} \gtrsim 12\,\text{TeV}$, and show that it is solved within flavor triviality models. Interestingly, our framework can induce a sizable differential $t\bar{t}$ forward-backward asymmetry, and leads to an excess of massive boosted di-jet events, which may be linked to the recent findings of the CDF Collaboration. This feature may be observed by looking at the corresponding planar flow distribution, which is presented here. Finally we point out that the celebrated standard model preference towards a light Higgs is significantly reduced within our framework.

Introduction. The Randall-Sundrum (RS) warped extra dimensional framework provides a solution to the hierarchy problem [1]. The most studied version of this class of models is the "anarchic bulk RS" scenario, where the standard model (SM) fields propagate in the 5D bulk, and the microscopic flavor parameters are generic. The SM gauge group is enlarged to contain a product of $SU(2)$ and discrete custodial symmetries [2, 3], thus greatly suppressing RS corrections to the electroweak (EW) observables. However, a closer look at this scenario shows that, despite providing a solution to the SM flavor puzzle [4], little hierarchies and CP problems remain, pushing the Kaluza-Klein (KK) scale of these models up to unnatural values. For instance, the contribution to electric dipole moments (EDMs) was found to be very roughly 20 times above the present bounds for an $\mathcal{O}(3\,\text{TeV})$ KK scale [5], the combined contribution to ϵ_K [6–8] and ϵ'/ϵ_K [9] requires a KK scale of $\mathcal{O}(6\,\text{TeV})$, and a careful EW fit to a subclass of these models (at the one loop level) [10] recently showed that a KK scale above $\mathcal{O}(4\,\text{TeV})$ is required. All this motivates trying to naturally decouple the flavor and CP issues, which have nothing to do with the EW fine-tuning problem, and analyzing the status of this framework when the EW scale naturalness is the main concern. This was the subject of [10], which studied the "flavor trivial" case where the flavor hierarchy is set by UV physics on the Planck brane [11]. The resulting bulk RS phenomenology turns out to be significantly modified, with a greatly improved EW fit allowing for a KK mass below 2 TeV [10], while the RS ϵ_K problem is absent.

The purpose of the present letter is to demonstrate that this class of flavor triviality models leads to exceptional collider phenomenology. We show that the same features that lead to a successful fit to the EW and flavor-violating observables, also yield unconventional signals. In fact, some of the observables discussed below have been already measured at the Tevatron in the context of the forward-backward asymmetry (FBA) in top pair production, a search for highly boosted tops and a study of the planar flow distribution of massive jets [12–16]. It is rather intriguing that some inconsistencies with the SM predictions have been observed. If confirmed at the LHC, they may support the presence of some sort of flavor triviality (for a complimentary study of multi-tops at the LHC see [17]). We also discuss how the bound on the Higgs mass is typically softened in our framework, and provide a quantitative analysis of the RS EDM problem, showing that it is naturally solved with flavor triviality.

The model. We work in a slice of AdS$_5$ space-time, whose fifth (conformal) coordinate z is bounded by two branes, at $R = M_{\overline{\text{Pl}}}^{-1} \sim (10^{19}\,\text{GeV})^{-1}$ in the UV and $R' \sim \text{TeV}^{-1}$ in the IR, where $M_{\overline{\text{Pl}}}$ is the reduced Planck mass. We use the notation $\epsilon \equiv e^{-\xi}$, where $\xi \equiv \log(R'/R)$. We impose a $SU(2)_L \times SU(2)_R \times U(1)_X$ gauge symmetry in the bulk, and assume that the Higgs field, H, is a bulk field with vacuum expectation value (VEV) $\langle H \rangle = vR'/R^{3/2}\sqrt{1+\beta}(z/R')^{2+\beta}$ with $v \simeq 246\,\text{GeV}$. The VEV localization in the bulk is set by β, and $\beta = 0$ corresponds to gauge-Higgs unified models. The SM fermions are embedded as $Q \sim (2,2)_{2/3}$, $U \sim (1,1)_{2/3}$, $D \sim (1,3)_{2/3} \oplus (3,1)_{2/3}$ and $L \sim (2,2)_0$, $E \sim (1,3)_0 \oplus (3,1)_0$.

We also gauge in the bulk the non-abelian part of the SM flavor symmetry $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$. The breaking of the flavor group occurs on the UV brane, and is shined towards the IR by some flavon scalar fields, Φ, whose VEVs are proportional to the 5D Yukawa matrices $Y_{U,D,E}$. Thus, in contrast to previous scenarios, we take the 5D Yukawas to be hierarchical (similar to the 4D picture), and set by unspecified UV physics. All flavor changing effects are then controlled by the SM Yukawa couplings, thus realizing the minimal flavor violation (MFV) ansatz.

Within this model, it is possible to find sweet spots in

the parameter space of the fermion bulk masses described by c_{Q^3}, c_t, c_b, c_{Q^i}, c_{U^i} and c_{D^i} ($i = 1, 2$, with universal first two generation masses) for the quark sector and c_L and c_E for the leptons (taken to be fully universal).

Sweet Spot. In order to quantify the phenomenological aspects analyzed below, we consider a specific set of parameters close to one of the sweet spots presented in [10]:

$$C_Q \simeq (0.50, 0.50, 0.02), \quad C_D \simeq (0.63, 0.63, 0.57),$$
$$C_U \simeq (0.15, 0.15, 0.48). \tag{1}$$

The related effective 5D Yukawa eigenvalues (which are accompanied by $\alpha_{U,D}$ when coupled to the Higgs, *e.g.* in the fermion masses) are:

$$\alpha_U Y_U \simeq (4.3 \times 10^{-5}, 0.021, 4.2), \; \alpha_D Y_D \simeq (0.01, 0.19, 0.45). \tag{2}$$

The corresponding 2σ EW bound on the KK scale is $m_{KK} \gtrsim 1.7\,(2.1)$ TeV for a six (one) parameter fit. In order to make this sweet spot consistent with flavor bounds, we can choose $\alpha_{U,D}$ such that the 5D bottom Yukawa becomes much bigger than the top one, *e.g.* $\alpha_{U,D} \simeq 4, 0.12$. This leads to down alignment: $[m_D, Y_D] \simeq 0$, which effectively removes all constraints coming from the down sector. Consequently, the above set of parameters complies with flavor, at the cost of a (natural) hierarchy of $\mathcal{O}(30)$ between the α's. Note that since the one-loop contribution to $\delta g_{Z\bar{b}b}$ at large $\alpha_D Y_D$ is not known yet [18], we conservatively consider only cases with $(\alpha_D Y_D)^2 \ll (\alpha_U Y_U)^2$ [10]. Relaxing this constraint would probably lead to a larger set of viable models where no significant hierarchy between the α's is required.

Electric Dipole Moments. We now analyze the constraints from null EDM searches. We consider the flavor triviality case and also derive a robust bound for the anarchic class of models. To date, the strongest bounds come from neutron, Mercury and Thallium EDM searches. We find that the neutron and Mercury EDMs [19, 20],

$$|d_n^{\exp}| \lesssim 2.9 \times 10^{-26}\, e\,\text{cm} \quad (95\% \text{ CL}),$$
$$\left|d_{Hg}^{\exp}\right| \lesssim 3.1 \times 10^{-29}\, e\,\text{cm} \quad (95\% \text{ CL}), \tag{3}$$

are of most relevance in our case. These observables are measured far below the QCD scale.

The neutron EDM is sensitive to the CP-odd dipole effective operator at the TeV scale $2i \times \mathcal{L}_{\text{eff}} \supset \sum_f d_f^E \bar{f} (\sigma \cdot F) \gamma_5 f$, where $f = d, s, e$ etc. stands for a fermion flavor and F is the photon field strength. We use the parton quark model (PQM) to relate the neutron EDM to this set of operators, since it is the only nuclear model including the strange quark contribution, which turns out to dominate in RS. The neutron EDM is then given by (see *e.g.* [21] and refs. therein)

$$d_n = \eta^E \left(\Delta_d^{\text{PQM}} d_d^E + \Delta_u^{\text{PQM}} d_u^E + \Delta_s^{\text{PQM}} d_s^E \right), \tag{4}$$

where

$$\Delta_{d,u,s}^{\text{PQM}} \simeq 0.75, \; -0.51, \; -0.23; \quad \eta^E \simeq 1.5, \tag{5}$$

and d_f^E are evaluated at the EW scale.

The mercury EDM is sensitive to several types of operators, but in the current work the leading contribution is from the chromo-electric dipole $2i \times \mathcal{L}_{\text{eff}} \supset \sum_f d_f^C \bar{f} (\sigma \cdot G) \gamma_5 f$, where G is the gluon field strength. The relation is [21]

$$d_{Hg} = 7 \times 10^{-3} e(d_u^C - d_d^C)/g_s, \tag{6}$$

where g_s is the QCD coupling and d_f^C are evaluated at 1 GeV.

Within RS, the dipole operator d_f^E is induced by a one-loop process with KK-quarks and a Higgs or a KK-gluon [5]. Since to leading order, the KK-gluon exchange diagram is proportional to m_D, hence real, the Higgs contributions are expected to dominate. The relevant RS amplitude has been calculated *e.g.* in [9], and the result is

$$d_f^E \simeq \frac{ev}{16\pi^2 m_{KK}^2} \times (\text{spurion})_f. \tag{7}$$

The chromo-electric dipole is given by Eq. (7), with a proper replacement of the electromagnetic coupling of the quark with its QCD coupling. Generically, the leading contributions have the following spurion dependence [5]:

$$(\text{spurion})_{d,s} = \left[F_Q^\dagger \left(a_N Y_D Y_D^\dagger + a_C Y_U Y_U^\dagger \right) Y_D F_D \right]_{11,22},$$
$$(\text{spurion})_u = \left[F_Q^\dagger \left(a_N Y_U Y_U^\dagger + a_C Y_D Y_D^\dagger \right) Y_U F_U \right]_{11}, \tag{8}$$

where $a_{N(C)}$ corresponds to the neutral (charged) Higgs exchanges, and F_X are spurion matrices whose eigenvalues f_{x^i} represent the IR projection of the quark zero-mode profiles: $f_{x^i}^2 = (1 - 2c_{x^i})/(1 - \epsilon^{1-2c_{x^i}})$. Note that for models with a bulk Higgs, corrections for its overlap with the zero-mode fermions should be taken into account in Eq. (8), as we do implicitly throughout the paper.

Below we provide the first robust quantitative bound on the anarchic case, for which we follow the approach of [9, 22]. We look for the weakest bound which simultaneously minimizes the contributions from $\epsilon_K \propto (Y_D^*)^{-2}$, where Y_D^* is the average value characterizing the anarchic 5D down Yukawa matrix, and $d_f \propto (Y_D^*)^2$. We find that the strongest EDM bound comes from Mercury via d_d^C. Conservatively, we focus only on the neutral Higgs exchange, which amounts to setting $a_C \to 0$ in Eq. (8) (since the charged Higgs contribution is proportional to $Y_U Y_U^\dagger$, it cannot be naively added to the neutral one or combined with ϵ_K). The corresponding one-loop contribution was calculated in [9, 22]

$$d_d^C \sim \frac{3 g_s m_d}{16\pi^2 m_{KK}^2} (Y_D^*)^2, \tag{9}$$

yielding[1]

$$d_{Hg} \sim 1.2 \times 10^{-27} \, (Y_D^*)^2 \left(\frac{\text{TeV}}{m_{\text{KK}}}\right)^2 e\,\text{cm}\,. \qquad (10)$$

Consequently, the resulting bound on the KK scale is

$$m_{\text{KK}} \gtrsim 6.2 \, Y_D^* \, \text{TeV}\,. \qquad (11)$$

Optimizing the bound in Eq. (11), w.r.t. Y_D^*, together with the ϵ_K bound: $m_{\text{KK}} \gtrsim 8.5 \, g_{s*}/Y_D^*$ TeV for a bulk Higgs with $\beta = 0$ [9] (where $g_{s*} \approx 3$ is the KK-gluon coupling, including one loop matching [22]), we find the lowest possible bound on the KK scale for the anarchic scenario to be

$$m_{\text{KK}} \gtrsim 12 \, \text{TeV}\,, \qquad (12)$$

obtained for $Y_D^* = 2.0$. Interestingly, assuming that the uncertainty in estimating the mercury EDM in Eq. (10) is $\sim 50\%$, the uncertainty on the combined bound in Eq. (12) is only $\mathcal{O}(10\%)$.

We now switch gears to discuss the flavor triviality case. In this model, due to the approximate down alignment the dominant contributions come from the charged Higgs exchange. In the down mass basis $(\text{spurion})_s$ can be written as

$$\left[D_L f_Q V^{QU} \lambda_U \lambda_U^\dagger V^Q \lambda_D F_D \right]_{22}, \qquad (13)$$

where f_X and λ_X indicate the diagonal forms of F_X and Y_X, respectively, while V^Q (V^{QU}) parameterizes the misalignment between Y_U and Y_D (Y_U and C_Q) and D_L is the left rotation to the down mass basis (see Appendix B in [10]). Within the RS linear MFV approximation (where $D_L = \mathbb{1}_3$), EDMs are only induced at the two-loop level [23, 24], similar to the θ-term in the SM. The leading contribution enters at one-loop order from subleading terms in the MFV expansion, that are proportional to $\left[Y_U Y_U^\dagger, Y_D Y_D^\dagger \right]$ [10, 25], and results in a suppression by $\delta \equiv Y_t^2/Y_b^2$ ($Y_{t,b}$ correspond to the 5D *bulk* top and bottom Yukawas, respectively). Hence, the dominant contribution to the EDM, which proceeds via Y_t, comes from

$$(D_L)_{23} \sim \delta \, V_{23}^Q, \quad V_{33}^{QU} \simeq 1, \quad V_{23}^Q \sim r_Q V_{ts}^{\text{CKM}}, \quad (14)$$

where V^{CKM} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and $r_Q \equiv f_{Q^3}/f_{Q^i}$. Another conservative assumption taken above is in omitting a factor of Y_b^2 divided by its NDA bound, which is necessary for the existence of

a phase in $(D_L)_{23}$. Combining all of the above, we estimate the s quark EDM:[2]

$$d_s^E \sim \frac{e\,m_s}{8\pi^2 m_{\text{KK}}^2} \left(V_{ts}^{\text{CKM}}\right)^2 Y_t^2 \delta \, r_Q^3\,. \qquad (15)$$

As a concrete example, we now analyze the sweet spot described above around Eqs. (1) and (2). Plugging these numbers, we find

$$d_n \sim 4.4 \times 10^{-27} e\,\text{cm} \simeq 0.15 \, d_n^{\text{exp}}\,, \qquad (16)$$

for $m_{\text{KK}} = 1.7$ TeV. In [10] we reported two more flavor sweet spots, which include a large 5D bottom Yukawa and different contributions to CP violation in B_s mixing. The neutron EDMs for these two sweet spots are roughly 80% and 110% of the experimental bound, while other EDMs are much lower than their corresponding bounds. Given the $\mathcal{O}(1)$ uncertainties in the associated calculations, both examples can be considered consistent with present EDM constraints.

Collider Phenomenology. The collider phenomenology of flavor triviality models is interesting, since light fermions can be composite. This stems from the fact that the EW fit prefers c_{U^i} to be as composite as possible, although the χ^2 dependence on this parameter is mild. As a result, together with a much lower KK scale, hadronic cross sections are enhanced.[3] Specifically, at the LHC, we expect the KK-gluon production cross section to rise from the fb regime for anarchic models to the pb one, making it accessible for early LHC discovery. Furthermore, the compositeness of the right-handed light quarks potentially leads to FBAs and to an excess of high-p_T top pairs at the Tevatron. Below we only focus on existing Tevatron data. We do not attempt here to provide a complete scan of the parameter space. Rather, to demonstrate our point that this framework leads to exciting phenomenology, we evaluate the observables related to the sweet spot given in Eq. (1).

The different properties of the KK-gluon compared to the anarchic scenario warrant a short discussion. First, the compositeness of some of the light quarks significantly enhances its production rate, as just mentioned. Conversely, this also increases Γ_{KK}, the KK-gluon width, such that[4] $\Gamma_{\text{KK}} \sim 0.3 \, m_{\text{KK}}$. However, since we will be

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[1] The overlap correction, which is implicitly included, is ~ 0.1 [9].

[2] We consider only the contribution from one of the charged Higgs diagrams, as the other (with the photon attached to the Higgs line [22]) is of the same order.

[3] Throughout this section we set the KK-gluon coupling to $g_{s*} \simeq 6$ by means of a localized kinetic term on the UV-brane, which is within the perturbative regime. As a result of the approximate down alignment, this is still consistent with flavor constraints.

[4] Decays involving one of the lightest KK resonances of the custodian fields, which obey $(-,+)$ or $(+,-)$ boundary conditions and are about 30% lighter than the KK-gluon, are suppressed by the EW symmetry breaking scale. Also, the lightest KK-

interested in energies which are more than two widths below the mass, it is justified to ignore effects related to the energy dependence of $\Gamma_{\rm KK}$ (see *e.g.* [30] and refs. therein for important running width effects for lighter resonances). Overall it is expected that the prospects for LHC discovery of the KK-gluon would be greatly increased, for example via an enhancement of boosted top pair production (see below). Finally, all of the above implies that this model should enhance the signal of dijet events, such that it may be detected or excluded in the future.[5]

We now show how this class of models can lead to a large $t\bar{t}$ FBA. Specifically, the asymmetry is enlarged when focusing on large $t\bar{t}$ invariant masses, as recently found by CDF [14]. The asymmetry observed at the Tevatron reads [12–14]

$$
\begin{aligned}
A^{t\bar{t}}_{450} &= (48 \pm 10 \pm 4.9)\%, \quad A^{\rm pred}_{450} = (8.8 \pm 1.3)\%, \\
A^{\rm lab}_{\rm CDF} &= (15 \pm 5.0 \pm 2.4)\%, \quad A^{\rm pred}_{\rm CDF} = (3.8 \pm 0.6)\%, \\
A^{\rm lab}_{\rm D0} &= (8 \pm 4 \pm 1)\%, \quad A^{\rm pred}_{\rm D0} = (1 \pm 2)\%,
\end{aligned}
\tag{17}
$$

where $A^{t\bar{t}}_{450}$ is the asymmetry in the $t\bar{t}$ rest frame for a top pair invariant mass $M_{t\bar{t}}$ larger than 450 GeV, as recently measured by CDF, and $A^{\rm pred}_{450,{\rm CDF,D0}}$ is the SM prediction for the corresponding observable. To make contact with the microscopic new physics model, it is convenient to replace the lab frame asymmetry with a $t\bar{t}$ frame one, reported by CDF to be [12] $A^{t\bar{t}}_{\rm CDF} = (16 \pm 7.2 \pm 1.7)\%$, while the SM prediction is $(5.8 \pm 0.9)\%$.

In RS, a differential asymmetry can be generated via $q\bar{q}$ annihilation into a KK-gluon, which subsequently decays to a top pair. This requires large axial couplings for *both* the $q\bar{q}$ and $t\bar{t}$ pairs to the KK-gluon, which arise from large differences between the left and right handed bulk masses. Since this is a feature of our model (as opposed to the anarchic case [33]), such an asymmetry is naturally induced.

At the partonic level, the asymmetry is given by [34, 35]

$$
\hat{A} \propto \beta_t \hat{s} \, |\mathcal{D}|^2 \, a_t a_q g_{s*}^2 \left[g_s^2 (\hat{s} - m_{\rm KK}^2) + 2 g_{s*}^2 \hat{s} v_t v_q \right], \tag{18}
$$

where $\mathcal{D}^{-1} \equiv \hat{s} - m_{\rm KK}^2 + i m_{\rm KK} \Gamma_{\rm KK}$. Here $\hat{s}$ and $\beta_t \equiv \sqrt{1 - 4 m_t^2 / \hat{s}}$ are the center of mass energy squared and the top quark velocity, respectively, in the $t\bar{t}$ frame, and $v_q \equiv -\xi^{-1} + \frac{1}{2}(f_{q_L}^2 + f_{q_R}^2)$ and $a_q \equiv \frac{1}{2}(f_{q_L}^2 - f_{q_R}^2)$ are the

vector and axial parts of a $q\bar{q}$ pair to the KK-gluon. We show in Fig. 1 the differential asymmetry as a function of $M_{t\bar{t}}$ for the above sweet spot parameters[6], compared to the recent CDF result [14]. Note, however, that the CDF data is not unfolded to the partonic level, so it cannot be directly compared to the flavor triviality expectation, yet the overall trend is similar. We also show NLO Monte Carlo predictions for the SM asymmetry at the partonic (black dashed curve) and detector (red circles with error bars) levels. Comparing these two curves, we learn that the unfolding factor is rather flat. Hence we expect that the general behavior of the unfolded distribution would be similar to the CDF one shown in Fig. 1, thus maintaining the shape agreement between the data and our prediction.
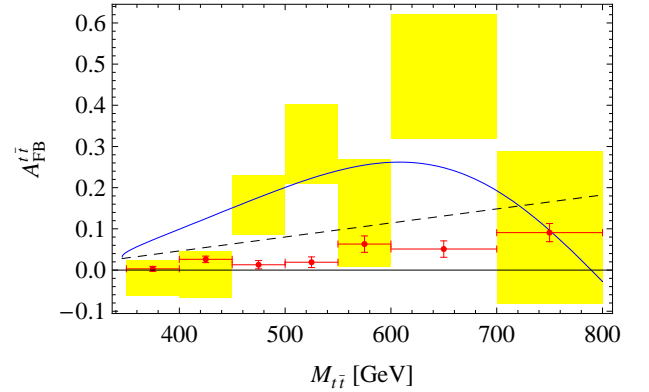

FIG. 1: Top pair differential forward-backward asymmetry $A^{t\bar{t}}$ as a function of $M_{t\bar{t}}$. Our prediction (including the SM) is in a solid blue line, while the CDF measurement (at the detector level) is described by the yellow shades [14]. The black dashed line stands for the SM partonic level prediction computed by MCFM, while the red circles with error bars correspond to the detector level prediction from MC@NLO [14].

As an explicit comparison, we note that for the sweet spot of Eq. (1) the asymmetry at $M_{t\bar{t}} > 450$ GeV is 19% (including the SM), which is more than 2σ below the CDF measurement in Eq. (17). Yet for the total asymmetry, our prediction is 12%, which is less than 1σ away from the CDF result. At the same time the total $t\bar{t}$ production cross section is 1.2σ below the measured value, while the differential cross section agrees with the CDF data [35].

Another important consequence of the flavor triviality approach is an enhanced cross section for the production of high-p_T top pairs, compared to the anarchic RS scenario (although the branching ratio for the decay of the

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quarks obeying $(+,+)$ boundary conditions, those with c=1/2, would have the same mass as the KK-gluon at tree level, while radiative corrections and EW symmetry breaking effects might render them marginally lighter. In any case, their effect on the KK-gluon width is negligible [2, 26–29].

[5] We found our model to be marginally consistent with recent LHC data [31, 32], based on a Monte Carlo simulation of the rate of central events (rapidity cut $|y| < 0.6$ at the partonic center of mass system) to non-central events ($|y| < 1.7$).

[6] We include the SM NLO contribution in a similar way to [35]. We estimate that the uncertainty from the non-universality of the k factors is $\mathcal{O}(10\%)$.

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